Prognostics

"Pre-state of the Art Novelty" or a "Pig with a Watch"

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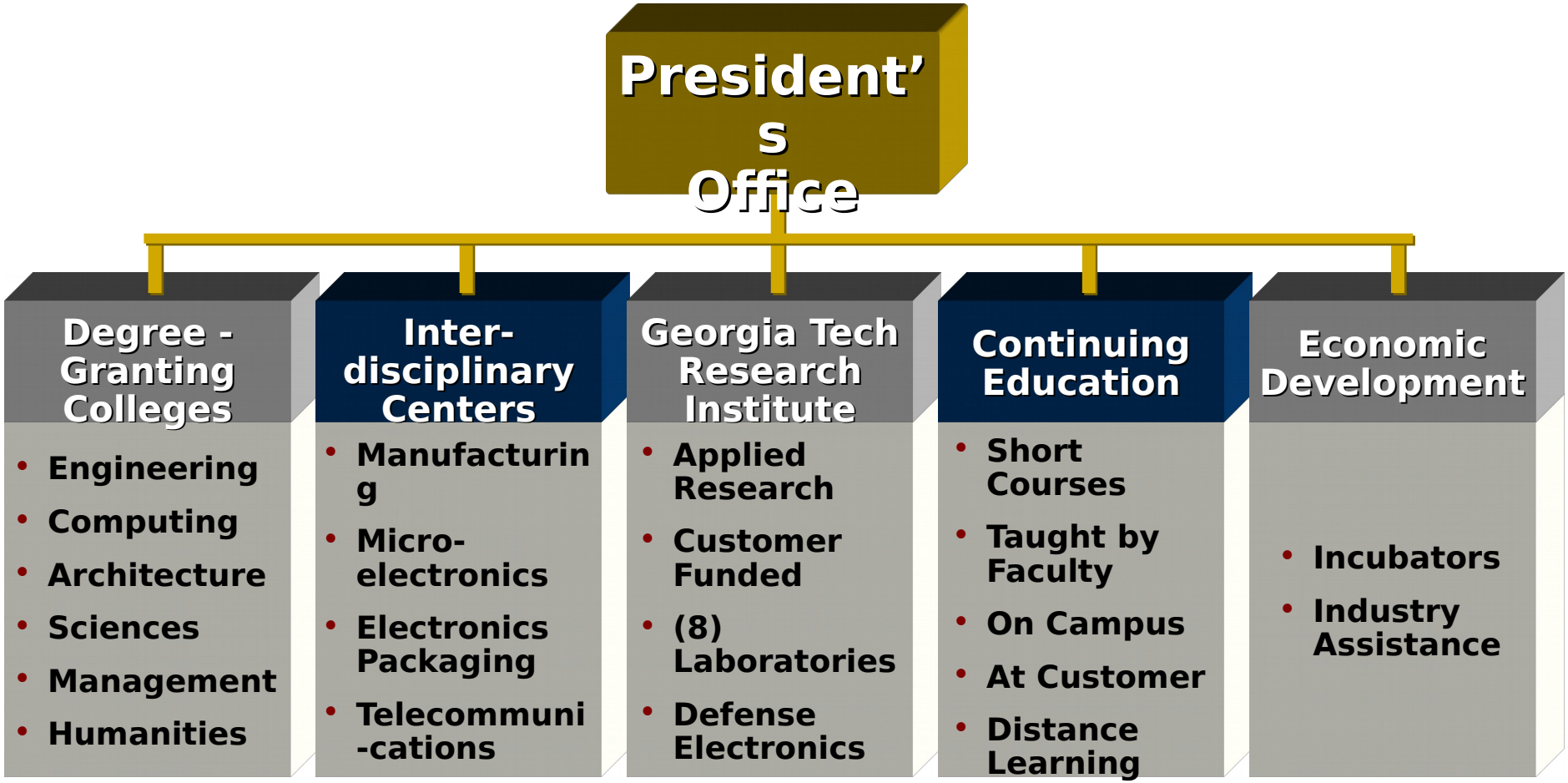
Overview

- Construct and Benefits of Prognostics
- Physics Based Development
- Application of FMECA Prognostics
- Evolution of Condition Based Maintenance

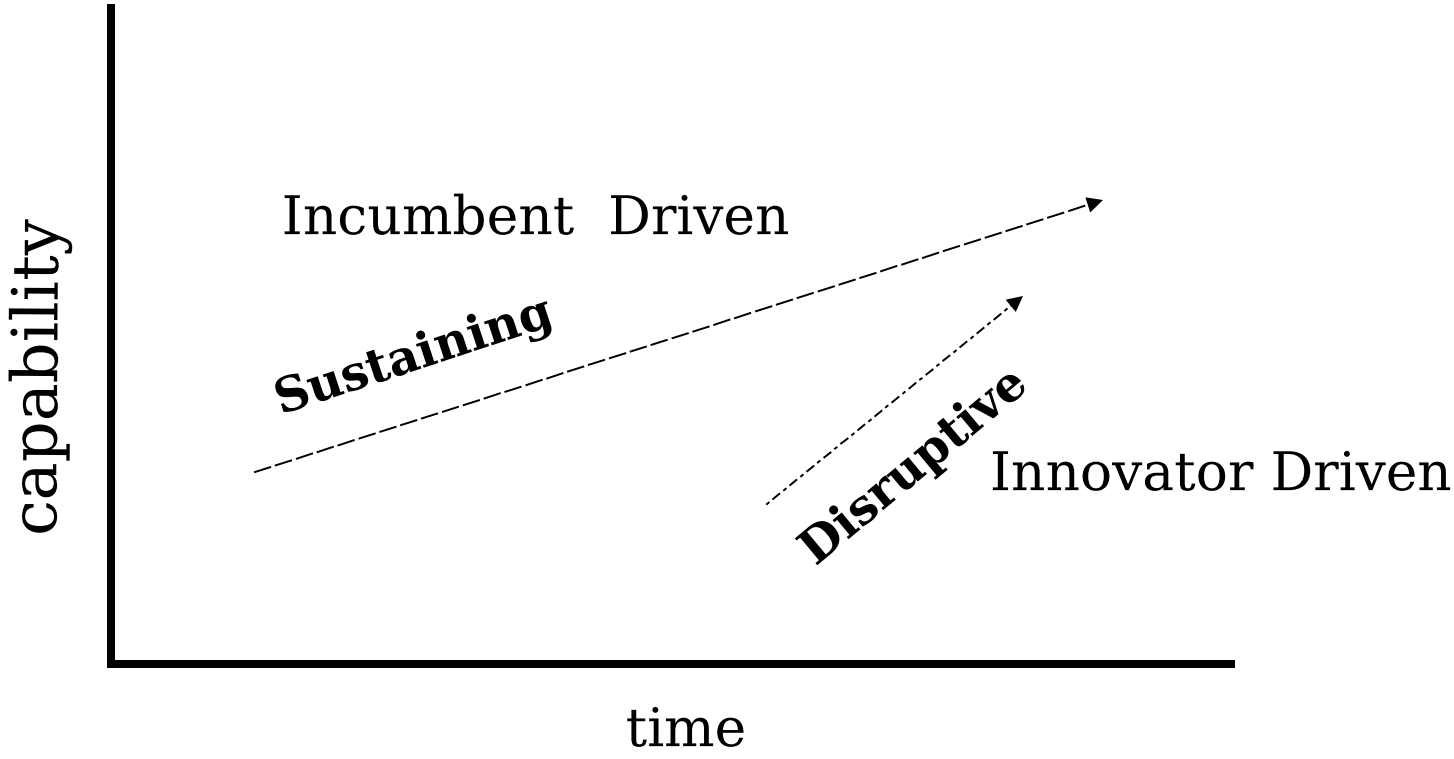
Major Units of Georgia Tech



Innovation Acceleration

- Growth occurs to firms with new market-qualified products and services
  - Changing Business Models – time to market
  - Systems Integrator vs Vertical Integrator view of Innovation
    - Profit structure/Capital investment
- Painkillers vs Enablers
  - Painkillers – find a problem and solve it
  - Enablers – enable a new capability for a customer
- Technology Acquisition Models
  - Organic Growth (Classic R&D Lab Model)
  - Acquisition of small firms (GE Model)
  - Consortium Development (NIST Model)
  - Technology Licensing (Predominant University Model)
  - Partnership Models (Emerging Public/Private)

Sustaining and Disruptive Technology Paradox and Challenges



Foundation for Prognostics

- Historical investment by ONR and Industry
  - MURI ($12M) 1996-2000 O&M Cost Reduction
  - Component and Systems Focus
- Examples of Prognostics interest underway within DoD
  - Army -- PM FMTV leadership role in vehicle platforms
    - Oil, chassis, fuel and hydraulic systems
  - USMC –focus on vehicle and logistics system
    - AAAV (GDLS)
  - AF – AFSPACE focus on infrastructure and satellites
    - Bearings, electronics. communications

- Commercial Industry focus on product warranty and process “down-time” cost reduction
    - Transportation/Automobiles
    - Appliances/Manufacturing

Related Work in Diagnostics / Prognostics / Condition Based Maintenance

- Fault Detection and Isolation of Space Station Rack Controllers (Boeing Aerospace Company)
- Diagnostics and Active / Adaptive Control of Jet Engine Compressor Failures (ONR)
- Diagnostics and Reconfigurable Control of Shipboard Electrical Distribution Systems (ONR and NAVSEA)
- Crack Detection (ONR MURI on Integrated Diagnostics)
- Health Monitoring of Autonomous Unmanned Vehicles (ARO)
- Sensor Fusion and Fault Detection in Electronics Manufacturing (MICOM, Electronics Industries)
- NOx Emissions Detection of Gas Turbines (GE)
- Condition Based Maintenance Program (Honeywell/ONR)
- Failure Detection and Control of Textile Processes (National Textile Center)
- Defect Detection and Control of Glass Processes (Ford Glass and DOE)
- Jet Engine Design and Control (GTC)

Diagnostics/Prognostics for Machine Health Maintenance

A four-day short course

by

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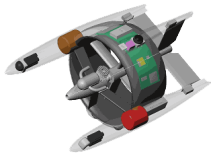
DoD Program Life Cycle Costs

- Defense Acquisition University statistic:
  - Weapon System Acquisition Cost: 28%
  - Weapon System O&M Costs: 72%

Prognostics attacks the O&M Costs of a System

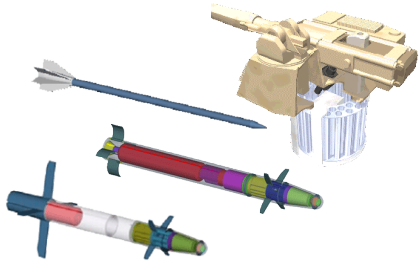
Future Combat Systems Technologies

UAV RSTA / Comm Relay

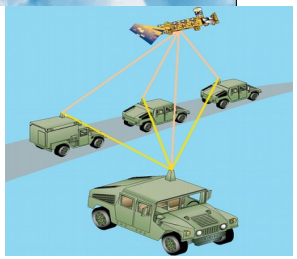


Adv. Sensors

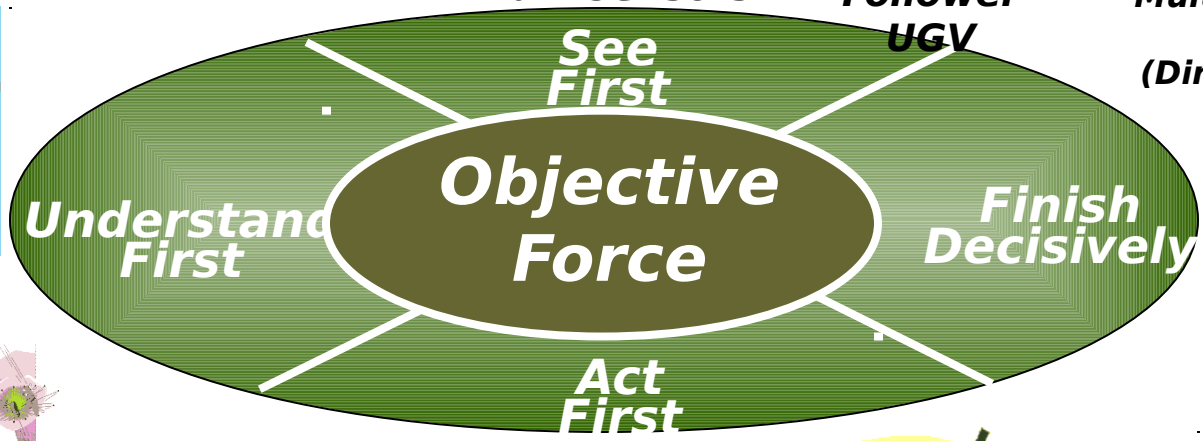
Follower UGV

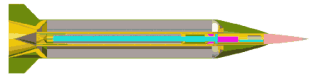


Multi-Role Armament & Ammo Suite (Direct & Indirect Fire)

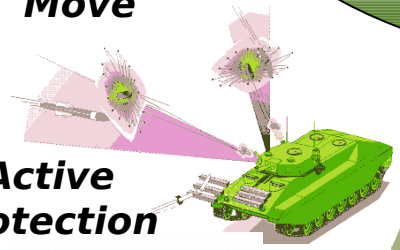


C3 On the Move

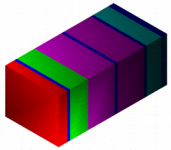




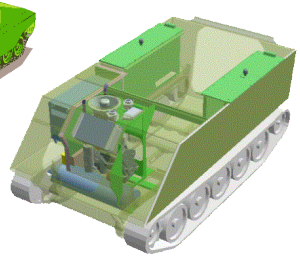
Compact Kinetic Energy Missile



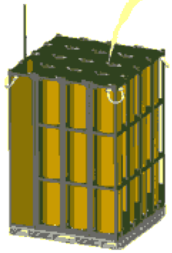
Active Protection



Integrated Armor



Hybrid Electric Propulsion



Networked Fires

OCSW

Technologies to Build FCS in this Decade

Desired Prognostics End States

- Advantages:
  - Leverage Diagnostics Capability
  - Life Condition Monitoring(Decay and Reset)
  - Economic Timing of Repair/Replace
  - Training Feedback/Correction
  - Design Modification (Spiral Development)
  - Plug and Play

Basic issue is the pathway to reach the end states!

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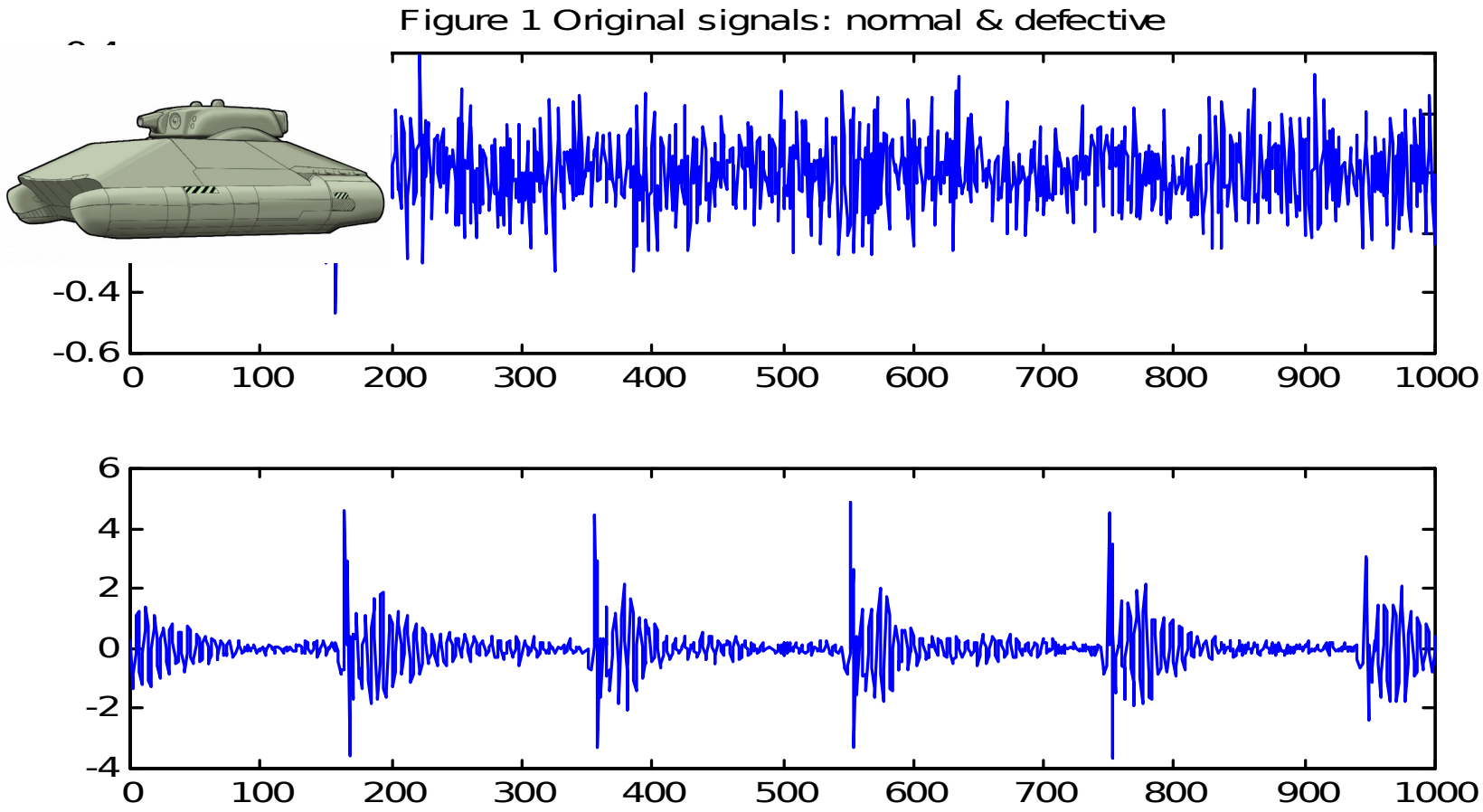
Building Blocks of Prognostics

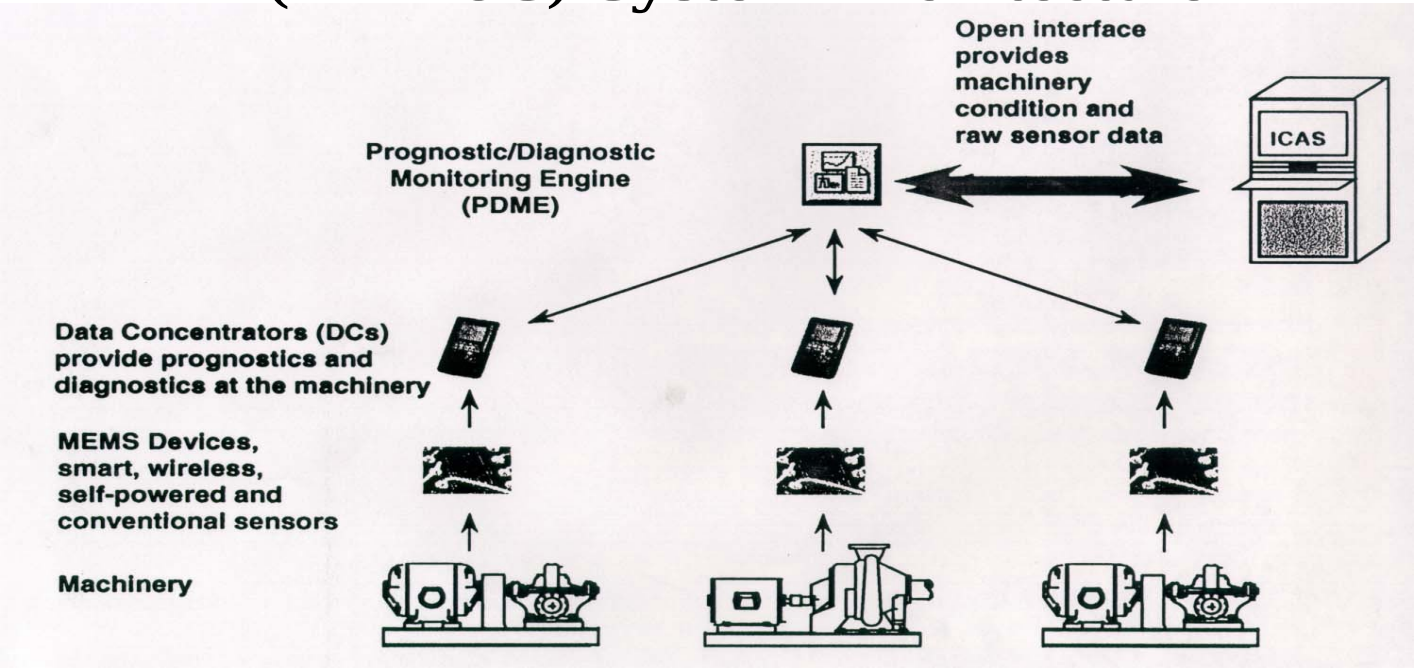
- Physics of Failure/Phenomenology
- FMECA
- Sensors (Dedicated and Virtual)
- Architectures
- Data Collection
- Algorithm/Processing
- Information Reporting(Enterprise)

Prognostics Systems Chain



Recent Advances in Technology

Machinery Diagnostic and Prognostic System (MPROS) System Architecture


Open interface provides machinery condition and raw sensor data
ICAS
Prognostic/Diagnostic Monitoring Engine (PDME)
Data Concentrators (DCs) provide prognostics and diagnostics at the machinery
MEMS Devices, smart, wireless, self-powered and conventional sensors
Machinery

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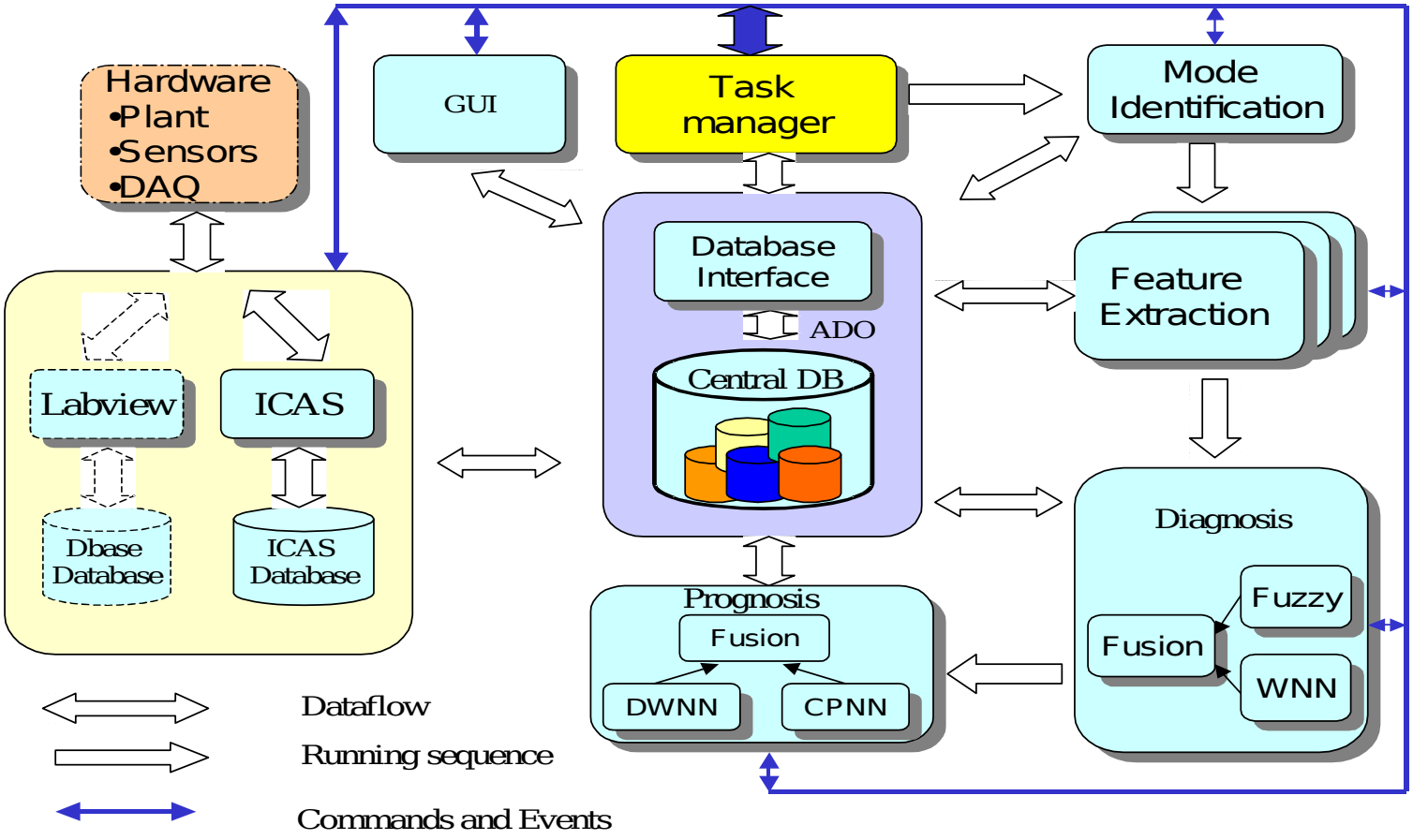
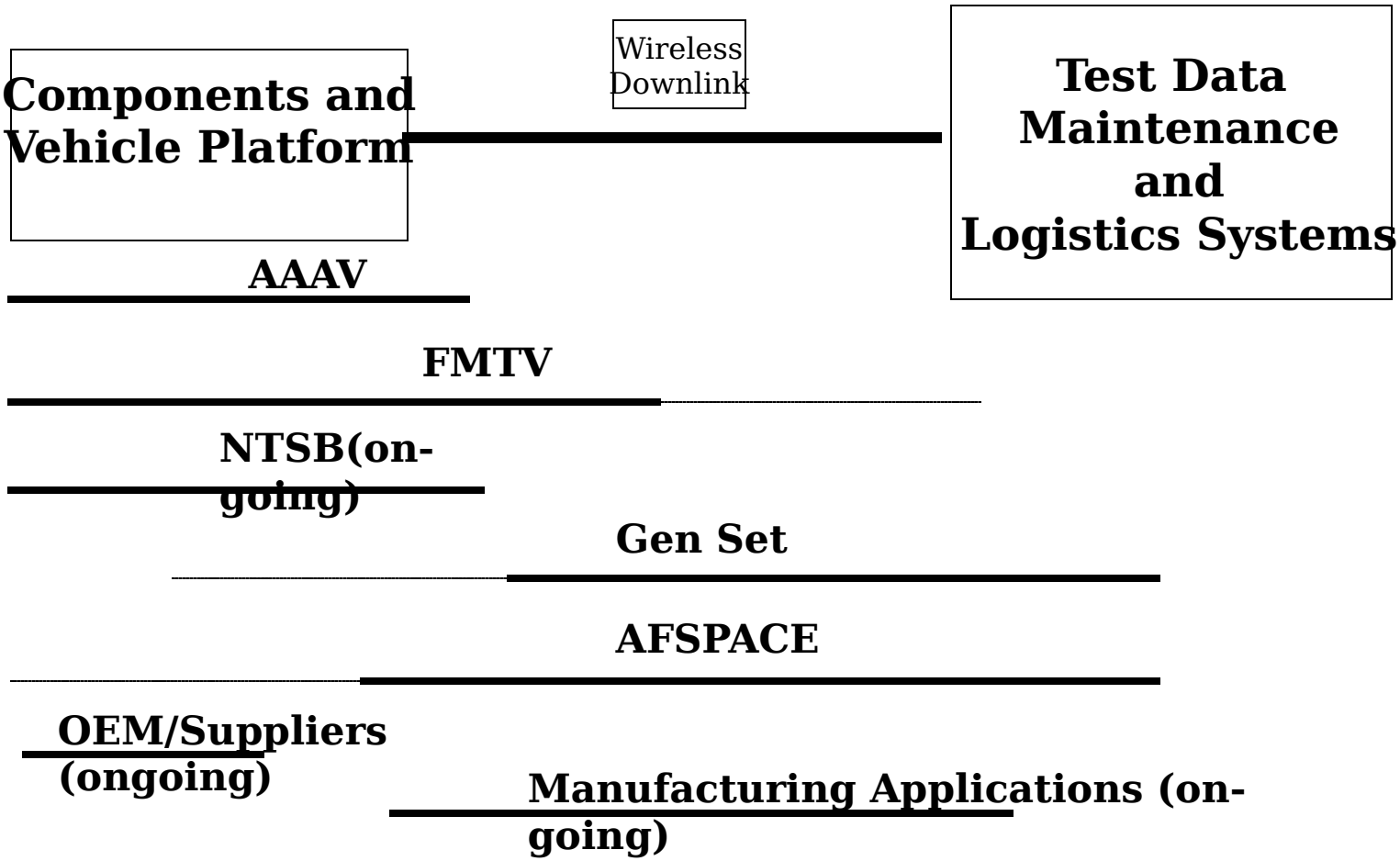
Recent Advances in Technology



Prognostics R&D Continuum

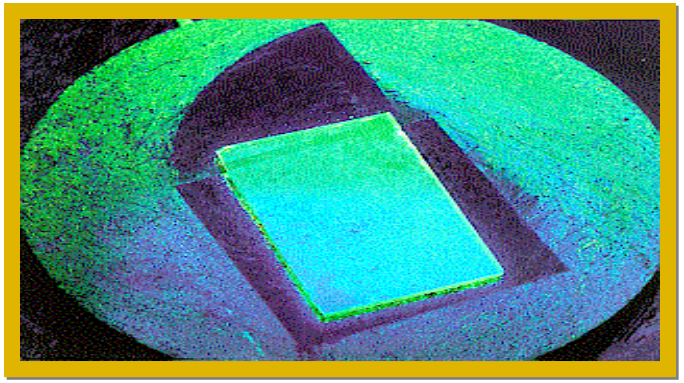


Prognostics Systems Leverage

- Prognostics provides proactive vehicle status information:
  - What duty-cycle has it been through?
  - How good is it?
  - When does it go into repair?
- Diagnostics often mis-labeled as prognostics
  - Diagnostics – detect negative effect – 1st step!!!
  - Prognostics – how long until the part fails? (proactive)
- Prognostics moves beyond diagnostic approaches
  - What does the signal mean? –phenomenology
  - How does signal relate to test data?
- Prognostics provides a new tool to the test community
  - Real time data
  - Modeling and Simulation validation

Prognostics Technology

- Scalable-Open Architectures
  - Digital Bus/Analog circuits/Wireless transfer
- Time-Series Data/Phenomenology
  - Statistical Relationships between parameters
- Low cost components
  - Sensors (MEMs)
  - Storage/Memory
- Algorithms
  - Genetic Algorithms/Fuzzy Logic
- Significant holes in tech base:
  - “glue-ware” for systems integration of components
  - confidence building demonstrations neede for maturation



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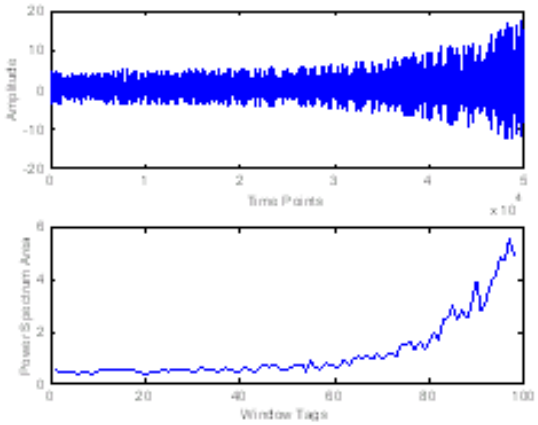
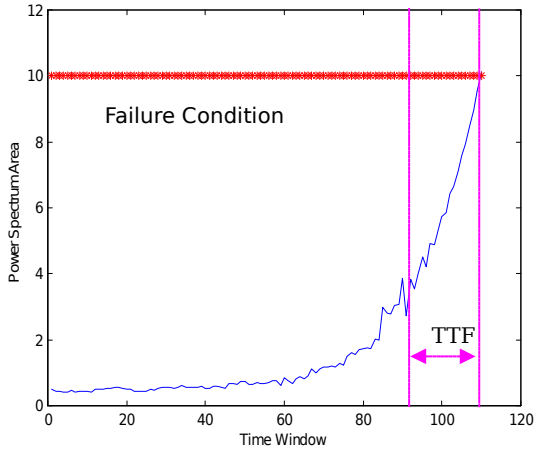
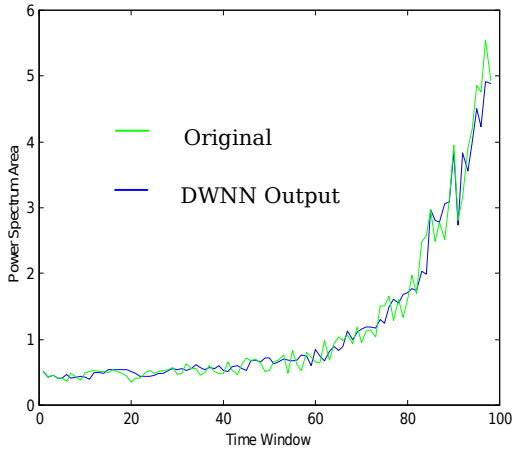
Prognostics

- Objective
  - Determine time window over which maintenance must be performed without compromising the system's operational integrity

Bearing Fault Prognosis

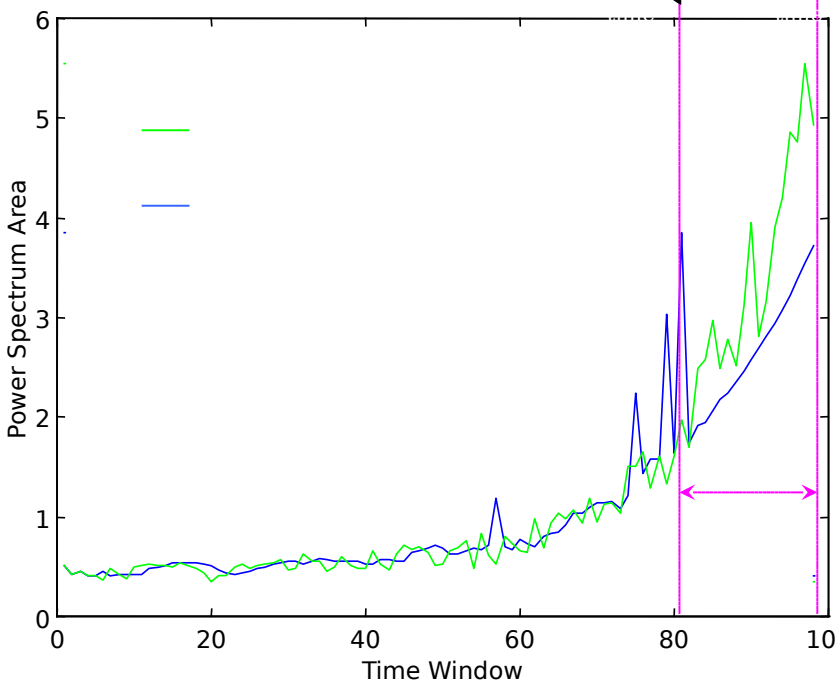


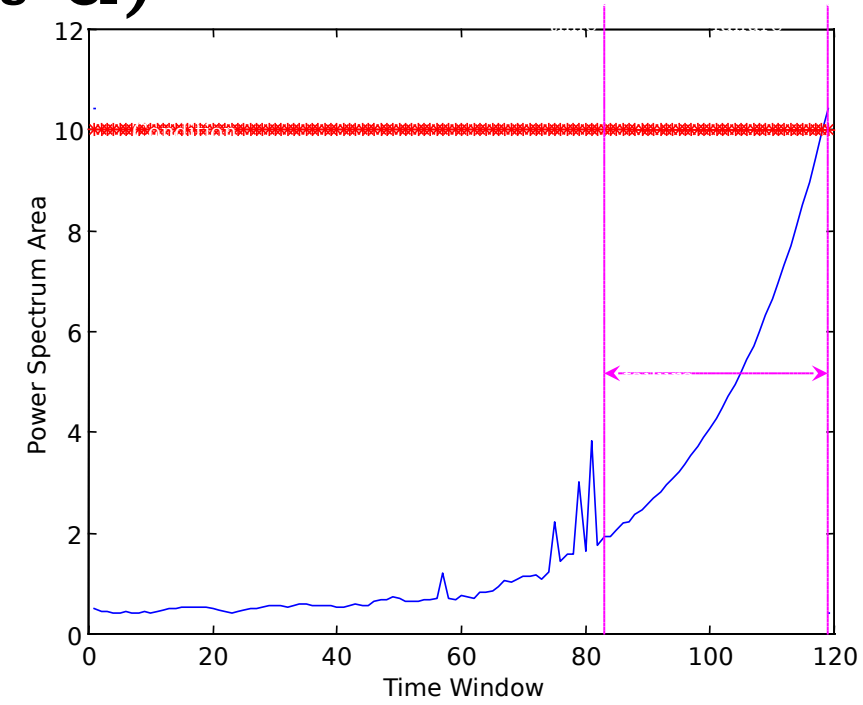




TTF = 19 time units

Bearing Fault Prognosis (cont'd)





Prediction up to 98 time windows using the trained WNN

Prediction of time-to-failure using the trained WNN

***time-to-failure* = 38 time windows**

FMECA

- Objective:
  - Determine Effects (Failure Modes) - Root Cause Relationships

    * A “Static” tool determined off-line

- Utility:
  - To assist in deciding upon the critical system variables and parameters
  - Instrumentation and monitoring requirements
  - Template generation for diagnostics

- Enabling Technologies:
  - Rule-based Expert Systems
  - Decision Trees
  - Fuzzy Petri nets

On FMECA

- Failure Mode and Effects Criticality Analysis conducted on Yorktown
- Failure Modes classified according to criticality, frequency of occurrence, etc.
- Used to direct/guide Diagnostic Algorithms

FMECA (cont'd)

- Occurrence :
  - Four classifications :
    - Likely
    - Probable
    - Occasional
    - Unlikely
  - Based on MTBF range of 1000 hours
  - Failure rate categories :
    - Category 1 : Likely greater than 100
    - Category 2 : Probable from 10 to 100
    - Category 3 : Occasional from 1.0 to 10
    - Category 4 : Unlikely less than 1.0

FMECA (cont'd)

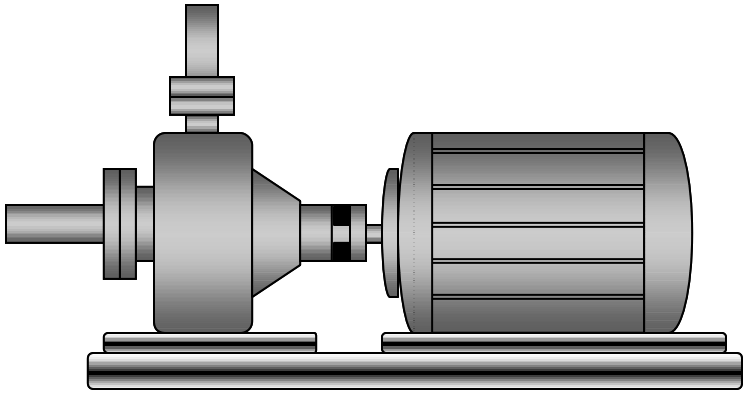
- Occurrence Probability :
  - Probability of a fault occurrence may be based on a classification category number from 1 to 4 (or possibly more divisions) with 4 being the lowest probability to occur
  - Separation of the four classes is determined on a log power scale
  - The classification number is derived based on failure occurrence for the particular event standardized to a specific time period and broken down into *likely, probable, occasional,* and *unlikely*.

FMECA (cont'd)

- Severity :
  - Severity categorizes the failure mode according to the ultimate consequence of the failure :
    - Category 1 : Catastrophic : a failure that results in death, significant injury, or total loss of equipment.
    - Category 2 : Critical : a failure that may cause severe injury, equipment damage, and termination
    - Category 3 : Marginal : a failure that may cause minor injury, equipment damage, or degradation of system performance.
    - Category 4 : Minor : a failure that does not cause injury or equipment damage, but may result in equipment failure if left unattended, down time, or unscheduled maintenance / repair.

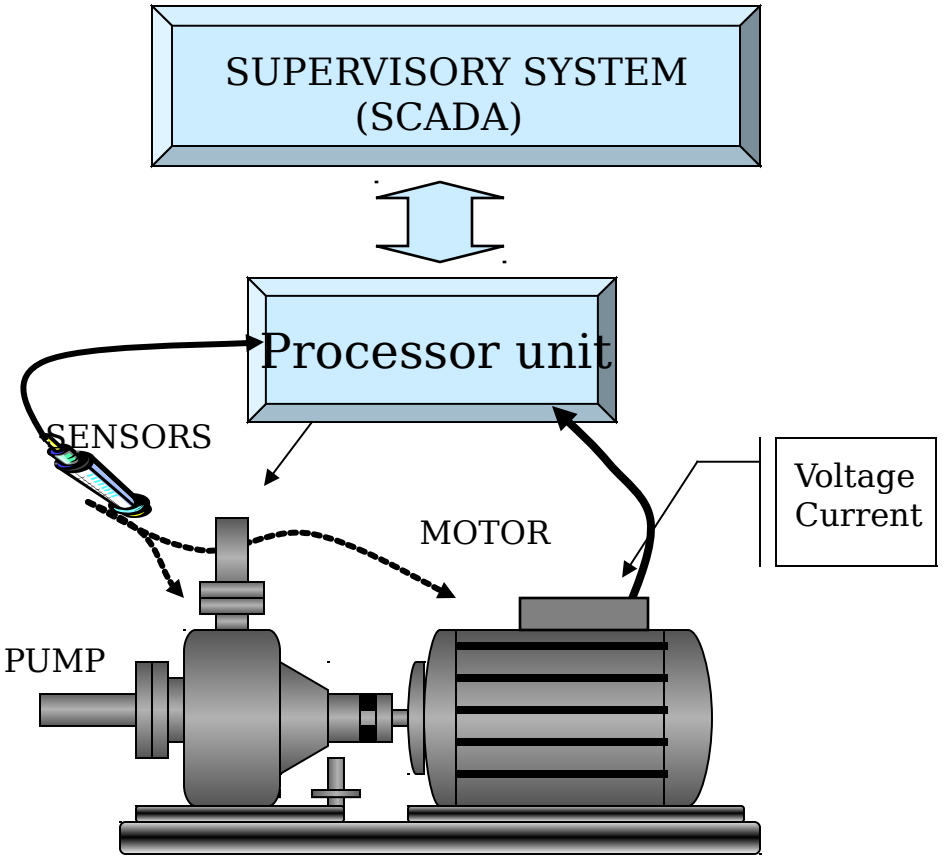
Failure Modes and Effects Criticality Analysis -*Testbed: Pump System*

- Problems, Root Causes, and Detection.
- Ranking and Maintenance.
- Actions.



Monitoring, Root Causes, and Detection

Temperature
Pressure
Vibrations
Currents
Voltages
Flow
Others



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Ranking of Fault Modes (Severity, Frequency and Criticality)

Frequency (F): **The rank is scaled from one to four as a function of how often the failure occurs.**

1 = Less than one in two years

2 = 1 to 3 every two years

3 = 2-6 per year

4 = More than 6 per year

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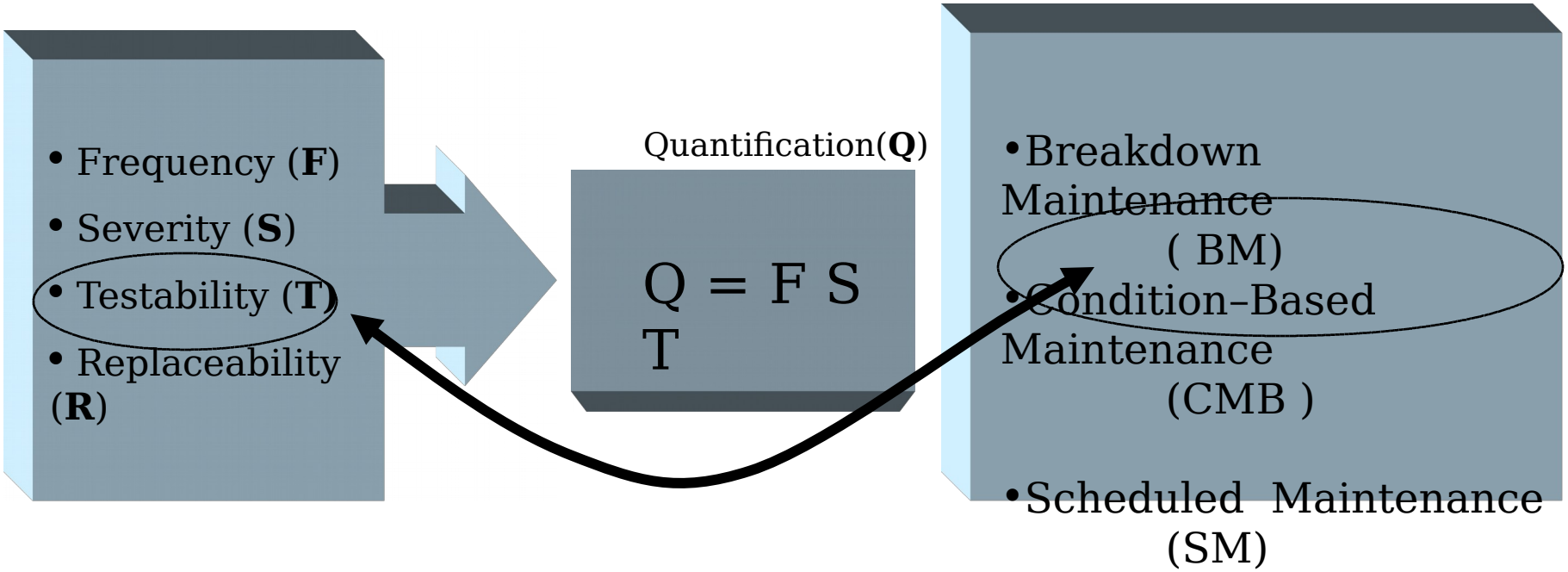
Ranking and Maintenance



Example of a FMECA Study

Testability

System	Components	Failure mode	Primary Cause	Symptoms	Evaluation					MF	Recommended action
					F	S	T	R	Q		
Pump	Non-return valve	No pump delivery	Non-return valve blocked open	Noise and overheat	2	3	4	1	24	SM	Regularly open and clean valve
	Bearing	Blistering Cracks Wear	Wear and tear Lack of Lubrication Overheat Misalignment	Noise and vibration High Temperature	3	2	2	1	18	CBM	Replacement
	Seal	Cracks Wear	Overheat No flow Wear and tear	Noise Leaked	2	3	2	1	12	CBM	Replacement
	Impeller	Pump blocked	Solid parts Corrosion	Noise No Flow	1	4	2	1	8	BM	Pump replacement
		Axle loose	Corrosion								

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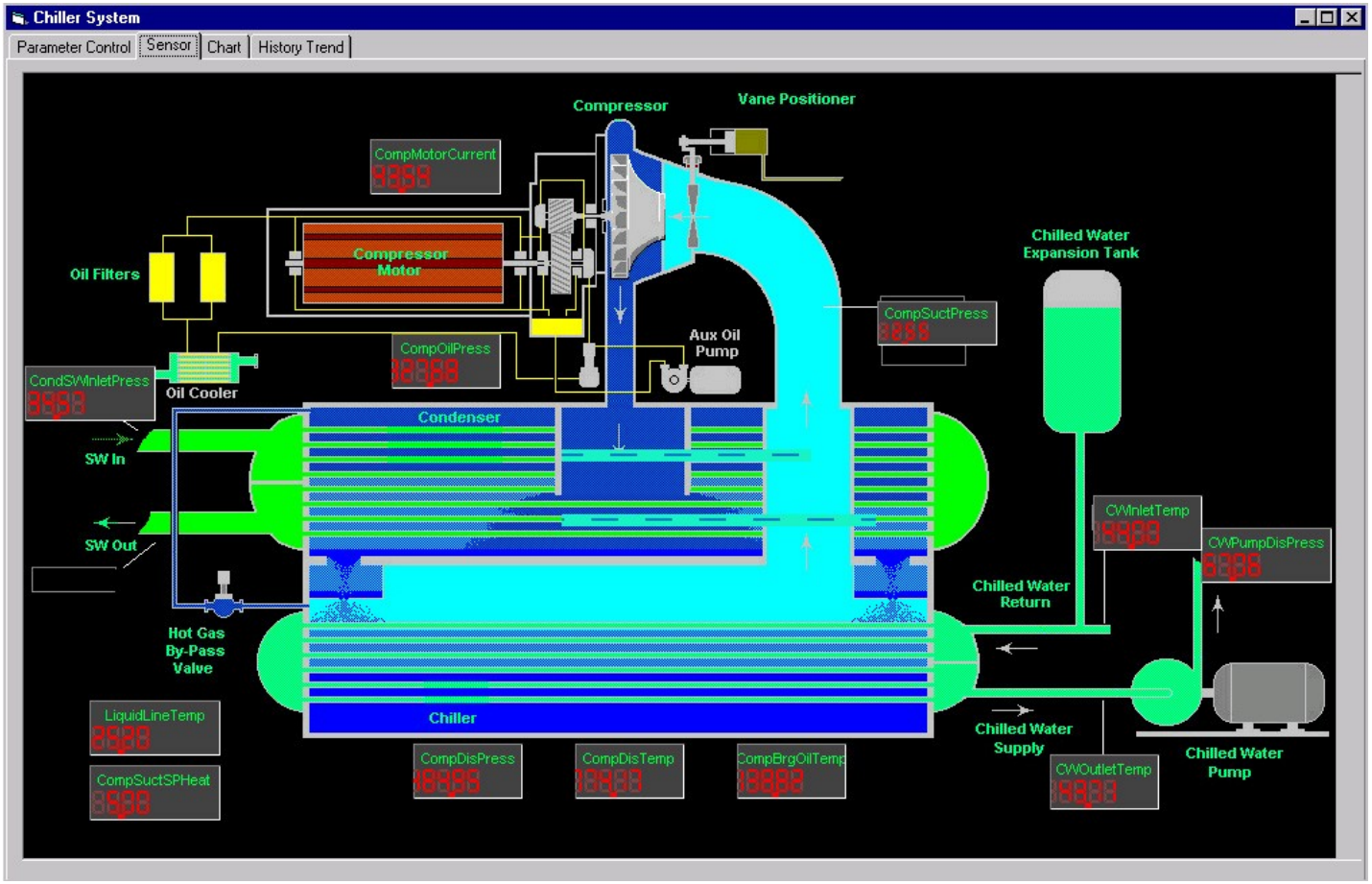
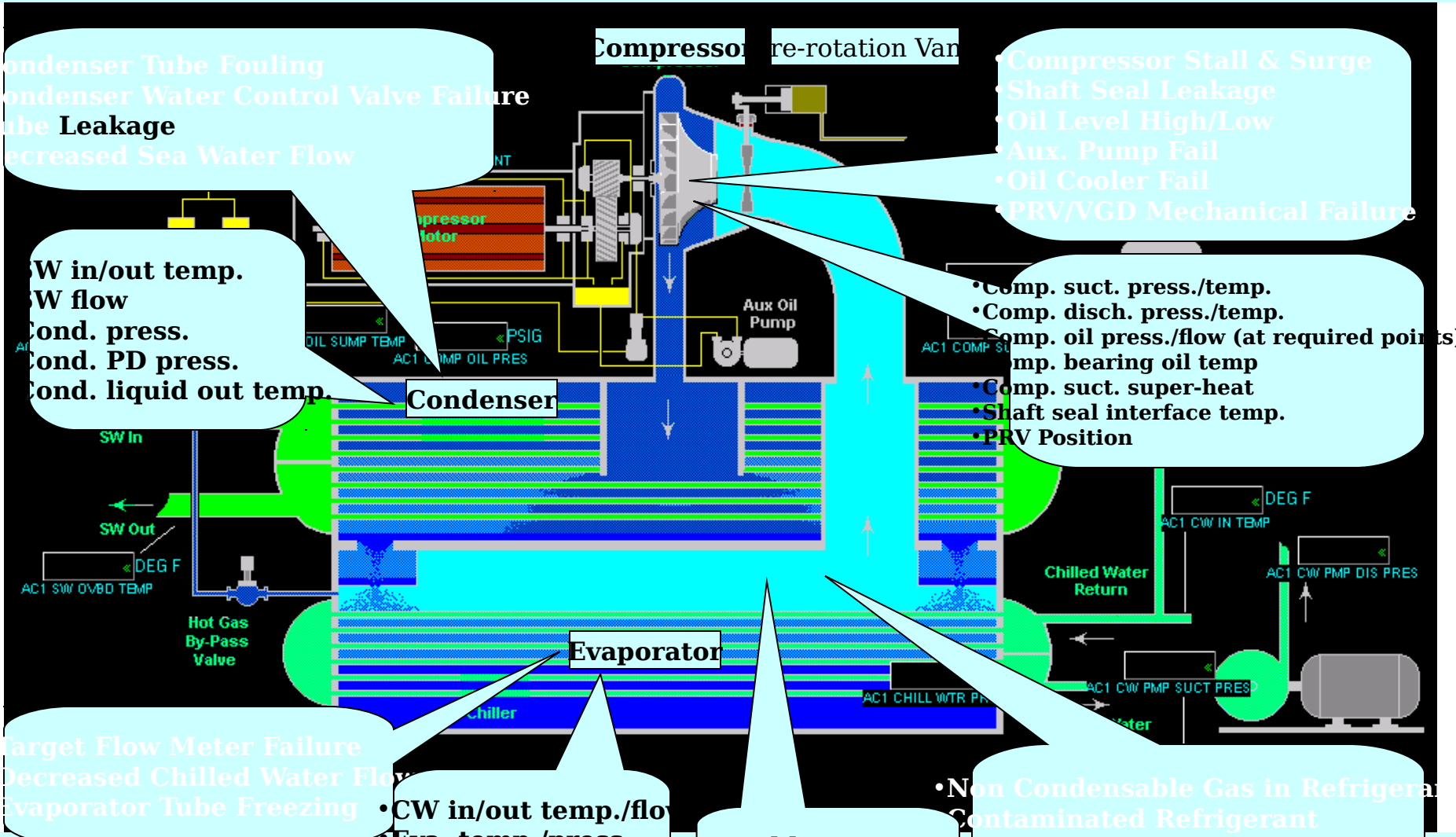
The Navy Centrifugal Chiller



Chiller Failure Modes



ondenser Tube Fouling
ondenser Water Control Valve Failure
ube Leakage
ecreased Sea Water Flow

•Compressor Stall & Surge
•Shaft Seal Leakage
•Oil Level High/Low
•Aux. Pump Fail
•Oil Cooler Fail
•PRV/VGD Mechanical Failure

W in/out temp.
W flow
ond. press.
ond. PD press.
ond. liquid out temp.

•Comp. suct. press./temp.
•Comp. disch. press./temp.
•Comp. oil press./flow (at required points)
•mp. bearing oil temp
•Comp. suct. super-heat
•Shaft seal interface temp.
•PRV Position

arget Flow Meter Failure
ecreased Chilled Water Flow
vaporator Tube Freezing

•CW in/out temp./flo
•Eva. temp./press.
•Eva. PD press.

•Liquid line temp.
•(Refrigerant weight)

•Non Condensable Gas in Refrigera
•Contaminated Refrigerant
•efrigerant Charge High
•frigerant Charge Low

Fault: Refrigerant Charge High

Occurrence: probable
Severity: critical
Testability:

Description: Due to overcharge during maintenance. The refrigerant is stored in the evaporator and under full load conditions should barely cover the tops of the cooler tubes. When refrigerant levels are high, the tubes are covered with to which refrigerant and less refrigerant is boiled off to the compressors. The overall effect is decreased efficiency which may result in loss of cooling. In addition, a very high charge level may result in the compressor sucking up liquid refrigerant droplets (instead of pure vapor) which can quickly erode the impeller.

Symptoms:

1) Refrigerant level very high
2) Increased full load ΔT across chill water
3) Low compressor discharge temp
4) High compressor suction pressure
5) High compressor discharge pressure
6) High compressor motor amps
OR
7) Compressor suction superheat less than 0˚F

Comments: Some type of level gage would be optimal for monitoring refrigerant charge. However, this could require modifications to the evaporator shell which would be impractical. Currently, have a site glass to view the level but not known to be a very good indicator of charge due to discrepancies in load conditions and chiller tube/site glass placement. Refrigerant levels should only be monitored during normal full load operating conditions (Since the boiling action within the cooler is much slower at partial loads than at full loads. The system will hold more refrigerant at partial loads than full loads).

Sensors:
Some type of level gage/sensor
Compressor suction pressure (10”Hg to 20psig)
Compressor discharge pressure (0 to 60psig)
Compressor discharge temp (30 to 220 ˚ F)
(Pseudo compressor suction superheat sensor)
Chilled water outlet temp (20 to 60 ˚ F)
Chilled water inlet temp (20 to 60 ˚ F)
Pseudo compressor suction superheat sensor
Pre-Rotation Vane Position

Fault: Condenser Tube Fouling

Occurrence: probable
Severity: marginal
Testability:

Description: Due to the corrosion caused from the sea water tube fouling results. Fouling can be caused from rust or sludge which accumulates in the tubes to reduce heat transfer. Also can be caused from a build up of mineral deposits known as “scale.” scale deposits are very thin but are highly resistant to heat transfer. Main focus for sea water tube fouling. Overall result is poor system performance which may result in loss of system cooling if left unattempted.

Symptoms:

1) A steady rise in compressor bead pressure with fouling over a period of time.
2) Accompanied with a steady rise in condenser liquid temperature, i.e., higher than normal compressor super heat (liquid temp minus discharge saturation temp above an alarm level of approx 5˚F)
3) Increasing temperature difference between sea water outlet temp and condenser liquid temp
4) Decreased sea water ΔT
5) Increased ΔP across condenser (decreases sea water flow)
6) Raised noise level in condenser due to flow
7) Increased compressor motor amps

Comments: Compressor bead pressure is the primary symptom of this fault. However, discharge pressure can vary widely depending on entering sea water temp and load. Typically, sea water temp is allowed to follow load, sea water temp, and possibly action of the sea water regulating valve. To accurately diagnose this fault the system must be free of air and non’s.

Sensors:
- Compressor discharge pressure (0 to 60psig)
- Compressor liquid temperature (50 to 150 ˚ F)
- Sea water outlet temp (20 to 120 ˚ F)
- Sea water inlet temp (20 to 100 ˚ F)
- (Pseudo compressor discharge subcool sensor)
- Condenser sea water inlet pressure (0 to 80psig)
- Condenser sea water outlet pressure (0 to 80psig)
- Condenser pressure
- Acoustic or accelerometer sensor on external condenser shell
- Pre-Rotation Vane Position
- Motor current sensing transformer

Fault: Evaporator Tube Freezing

Occurrence: occasional
Severity: critical
Testability:

Description: During low load conditions not enough heat is absorbed from the incoming chilled water and tube freezing may result. Freezing in the chiller tubes can result in tube rupture and contamination of the refrigerant system leading to major repairs and down times. Evaporator tube freezing has the same effect as fouling of the tubes due to foreign contaminants (raw occurrence for the chiller tubes). In addition, monitoring for low heat load can be accomplished by this same means.

Symptoms:

1) Decreasing evaporator refrigerant temperature (compressor cut out switch at 34˚F)
2) Decreasing chilled water out temp (slowly decreasing below 44˚F)
3) Excessively low compressor suction pressure (below 3”Hg)
4) Low compressor discharge pressure
5) Increased ΔP across evaporator (decreases chill water flow)
6) Low evaporator pressure
7) Low compressor motor amps

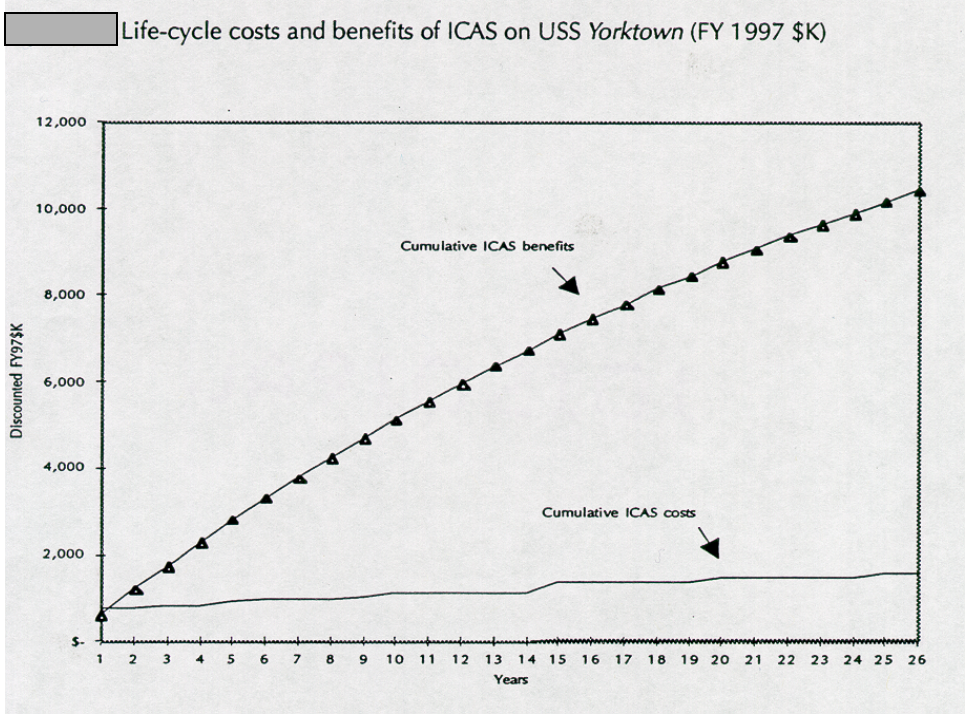
Comments: All symptoms above are assuring PRV’s are completely closed. If vanes were not found to be completely closed, may be a PRV linkage, actuator, sensor, or control problem.

Sensors:
Compressor discharge pressure (0 to 60psig)
Compressor suction pressure (10”Hg to 20psig)
Evaporator liquid temperature (20 to 60 ˚ F)
Chilled water outlet temp (20 to 60 ˚ F)
Chilled water inlet temp (20 to 60 ˚ F)
Evaporator chilled water inlet pressure (0 to 80psig)
Evaporator chilled water outlet pressure (0 to 80psig)
Evaporator pressure
Pre-Rotation Vane Position
Motor current sensing transformer

Condition Based Maintenance

The Opportunity

Condition Based Maintenance (CBM) promises to deliver improved maintainability and operational availability of naval systems while reducing life-cycle costs


Life-cycle costs and benefits of ICAS on USS *Yorktown* (FY 1997 $K)
Discounted FY97$K
12,000
10,000
8,000
6,000
4,000
2,000
$-
Cumulative ICAS benefits
Cumulative ICAS costs
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
Years

The Challenge

Prognostics is the Achilles heel of CBM systems - predicting the time to failure of critical machines requires new and innovative methodologies that will effectively integrate diagnostic results with maintenance scheduling practices

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Condition Based Maintenance

- Objective
  - Determine the “optimum” time to perform maintenance
- Problem Definition
  - A scheduling problem – schedule maintenance timing to meet specified objective criteria under certain constraints

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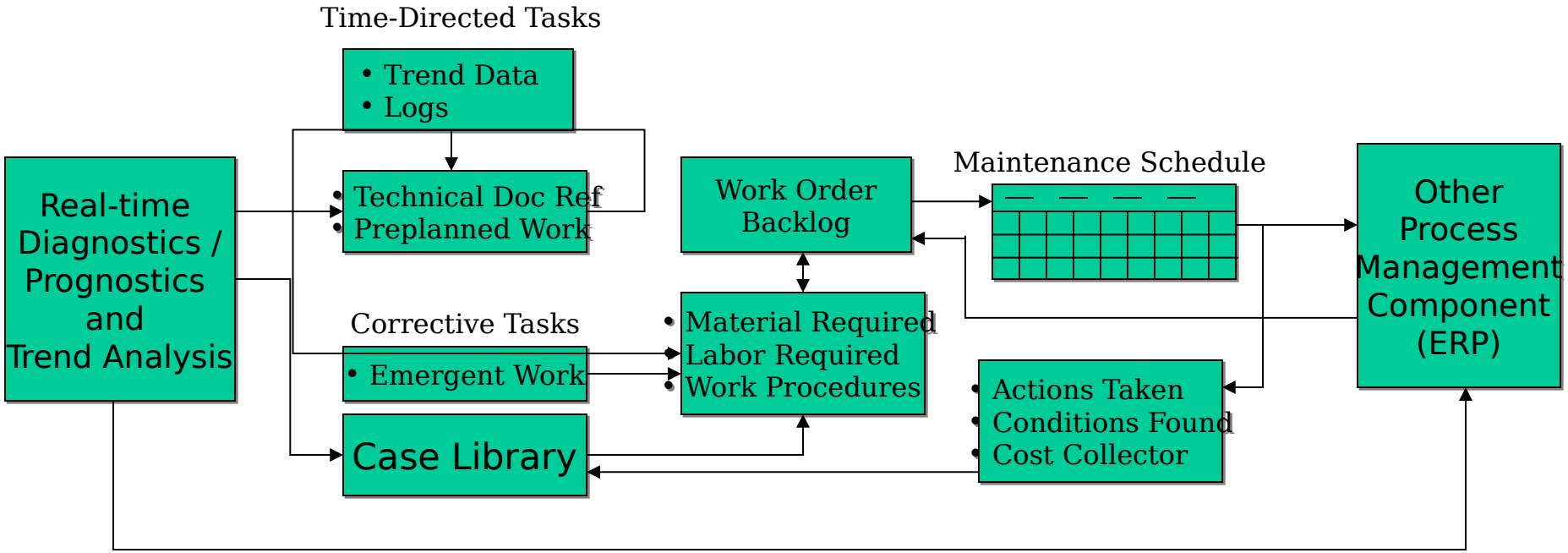
Condition Based Maintenance

- Major Objective
  - Extend system life cycle as much as possible without endangering its integrity
- Enabling Technologies
  - Various Optimization Tools
  - Genetic Algorithms
  - Evolutionary Computing

A Maintenance Management Architecture



Enabling Technologies

- Genetic Algorithms for Optimum Maintenance Scheduling
- Case-Based Reasoning and Induction
- Cost-Benefit Analysis Studies

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Challenges and Opportunities Ahead

- **Standards and Interface Development**
- **Development of Phenomenology**
  - Electronics
  - Software
- **Platform segmentation** (Systems Engineering Approach)
  - FMECA and sensoring (Prime/OEM)
  - Data analysis and reporting (Service Company)